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EFFECT OF MECHANICAL STRESS ON THE DIELECTRIC
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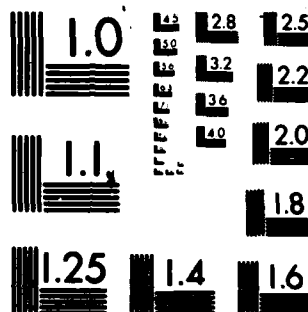
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Effect of Mechanical Stress on the
Dielectric Properties of Wood

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ABSTRACT

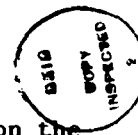
> The effect of mechanical stress parallel to the electric field on the polarizability (dielectric constant) and equivalent parallel conductance of wood was studied as a possible means for monitoring drying stresses. For electric and mechanical stress parallel to the grain, the effect was observable in wood that was moisture equilibrated at 65% percent relative humidity or greater, but was rather small and variable and drifted considerably with time. For stresses perpendicular to the grain, the effect was nearly nonexistent when the mechanical stress was no greater than the proportional limit. The effect also was essentially nonexistent for wood at moisture content lower than about 7%. The effect was generally larger at lower frequencies and was practically negligible at frequencies as high as 100 kHz. These results indicate that dielectric measurements are not feasible as a measure of mechanical stress in wood.

Keywords: Dielectric properties, dielectric constant, conductance, resistance, mechanical stress, compression, tension.

Effect of Mechanical Stress on the
Dielectric Properties of Wood

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INTRODUCTION

A major source of drying degrade in lumber is internal stress resulting from moisture gradients. Drying schedules are designed to provide the best compromise between the desire for fast drying and the need to keep drying stress low enough to avoid damage to the wood. It seems clear that if the drying stresses could be measured continually as the wood dries, this information would be ideal for controlling the drying schedule. This study tested the feasibility of estimating drying stresses from measurement of dielectric properties of the wood as it dried.

BACKGROUND

The change in magnetic permeability of ferromagnetic materials due to mechanical stress is recognized, and even has a name--the Villari effect. The analogous change in dielectric constant of polar solids due to mechanical stress is much more obscure; it has no name and is practically unmentioned in the basic literature on dielectric properties of solids (Debye 1945; Smyth 1955; Von Hippel 1954). There is, however, theoretical reason to expect the dielectric constant of polar solids to be affected by mechanical stress, due to the reorientation and change in freedom of motion of molecular dipoles as the material is strained.

Most experimental and theoretical consideration related to this phenomenon has focused on stress birefringence (the change of index of refraction under stress) of transparent solids at optical frequencies (Braybon 1953; Crawford and Kolsky 1951; Treolar 1947). In principle,

¹Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

however, the theory is not restricted to optical frequencies; the polarizability of the molecule in two or three principal directions is considered, along with the effect of orientation of the molecules on the overall polarizability. Further, limited experimental work has been reported on this phenomenon at lower frequencies (Scott 1935), which generally shows that compressive stresses tend to reduce the polarizability (dielectric constant) of polar solids. Iida and Fukuyama (1981) reported slightly enhanced dielectric constant and loss factor parallel to the grain in wood that had developed a tension set (across the grain).

In addition, while attempting to measure tensile strain in thin gluelines by measuring the change in capacitance between the metal adherends bonded by the glue, I have observed that with some rubbery, high-polymer glues the capacitance of the glueline actually increased as it was strained in tension. This clearly resulted from a substantial increase in the dielectric constant of the glue as it was stretched, overcoming the effect of reducing the density of the glue.

It has been demonstrated that wood is a strongly polar solid, at least when sufficient moisture is present (James 1975). At frequencies below about 300-1000 Hz, the predominant mechanism of polarization in moist wood appears to be interfacial, where charge accumulates at internal discontinuities. At middle frequencies, up to about 30-100 kHz, the polarization is predominantly molecular dipole, and, as the frequency increases, the mechanism shifts to atomic and then to electronic polarization. The general theoretical factors mentioned earlier, plus pertinent experimental data, suggest that the dielectric properties of wood should be modified by mechanical stress, at least where molecular polarizations predominate.

This phenomenon in wood would be expected to be small in comparison to the effect of moisture content (MC) and frequency. The purpose of this study is to attempt to determine the nature and magnitude of the effect of mechanical stress on the dielectric constant and equivalent parallel conductance of wood, and to determine the interactions of these effects with frequency and MC.

EXPERIMENTAL

Apparent capacitance and parallel conductance of specimens were measured both while they were stressed and unstressed. The dielectric constant is proportional to the capacitance, and equivalent parallel conductance is calculated from measurement of loss tangent. Both tensile and compressive stresses were considered. Principally, the stress was parallel to the nominal direction of the electric field; "nominal" because for one type of specimen the electric field was a fringe field, and therefore deviated somewhat from unidirectional. Also, a few exploratory measurements were made with the electric field perpendicular to the mechanical stress.

Data were taken at frequencies of 0.020, 0.10, 1, 10, and 100 kHz, all at a temperature of 80° F. Specimen material was conditioned to equilibrium at humidities of 30, 65, 80, and 90% at 80° F, giving approximate equilibrium MC values of 6, 12, 16, and 20%. Data were obtained with the mechanical and electric stresses along each of the three principal directions (longitudinal, radial, and tangential). Two species, Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and a white oak (Quercus sp.), were included. Three replicates of each specimen type were made.

Specimens

Two types of specimen were used. One was a wafer, 3/8 by 2 by 2-3/4 inches (fig. 1). Stress was applied along the longest dimension. Electrodes were two 1/8-inch-wide bands of silver-loaded conducting paint girdling the narrow cross section, 1/2 inch apart. One band was at the middle of the specimen; this was used as the ungrounded electrode. The other band was grounded. Connection to the electrodes was through solid copper wire clips pressed onto the specimen directly over the bands of silver paint and secured by more of the paint.

The ends of the specimen were coated for about 1/2 inch with polyurethane varnish to retard moisture change. The rest of the specimen was wrapped in a strip of plastic film secured by masking tape. The electrode clips poked out through the plastic. These specimens were designed to be stressed mechanically in either tension or compression.



Figure 1.--Specimens used in this study. Left: A large specimen before the central part was wrapped in plastic film, showing the silver paint electrodes. Center: A small compression-only specimen, also before being wrapped in plastic. Right: A large specimen showing the plastic moisture barrier wrap. (M83 0222-7)

The other type of specimen was a small block, $3/8$ by $1/2$ by $3/4$ inch (fig. 1). The $3/8$ - by $3/4$ -inch faces were coated with the silver paint and the other surfaces of the specimen wrapped in plastic film. These specimens could be stressed only in compression. These specimens were made because they located the mechanically stressed wood in a more nearly parallel electric field and could be loaded to a higher stress level.

Three replicates of each specimen type were made, each group of three having one of the three principal growth orientations in the direction of the applied mechanical stress.

Loading Device

Mechanical stress was applied to the specimens by a small vise with one clamp that could be moved by a lever (fig. 2). A 10-lb weight could be located at various positions along the lever to vary the force. The other clamp of the vise was adjustable but was fixed for taking data on a given

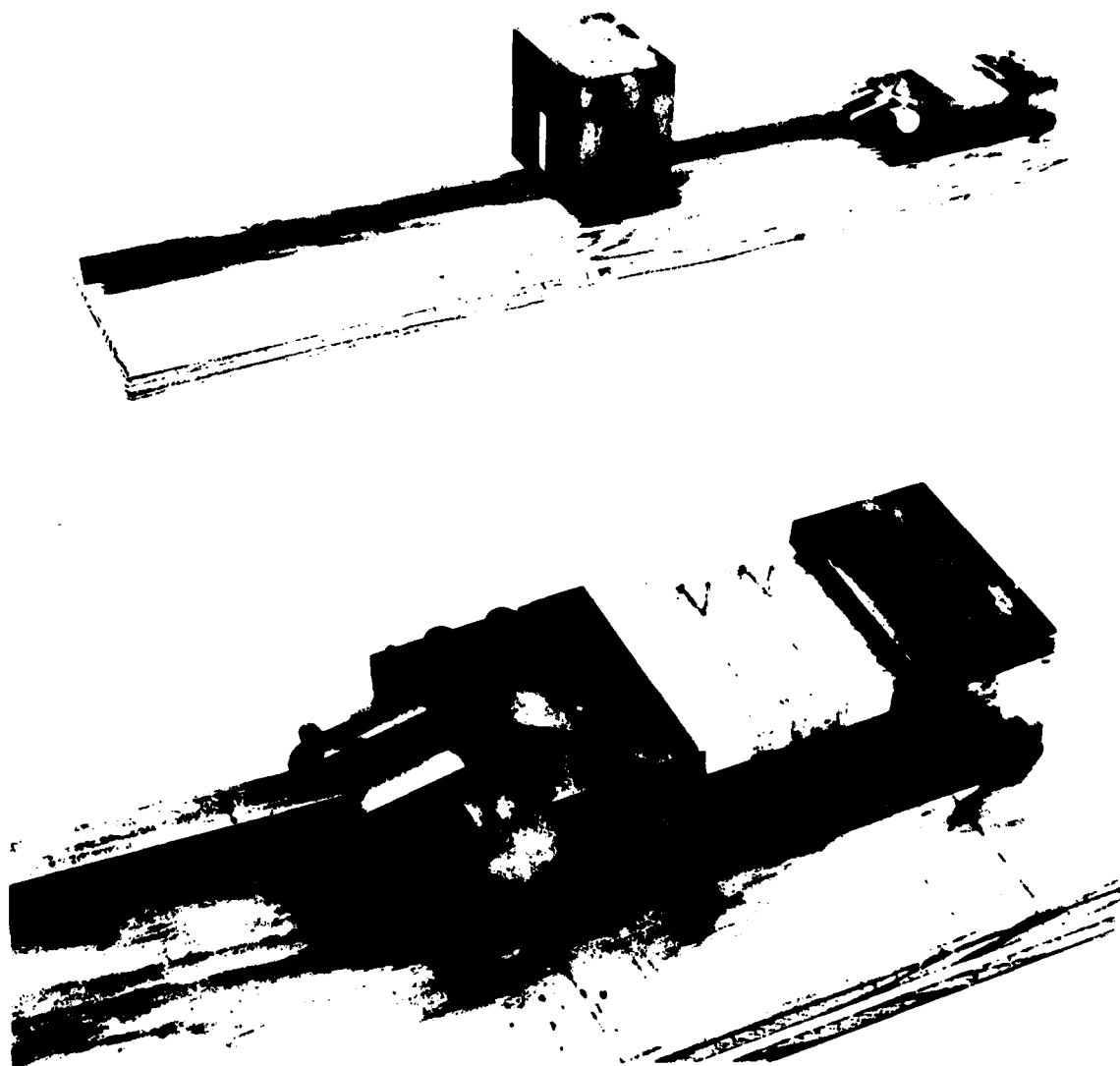


Figure 2.--Two views of the loading vise used to apply either tension or compression stress to the specimens.
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specimen. The vise could be changed from compression to tension by changing the location of the fulcrum of the main lever. Tension grip was assured by clamping surfaces consisting of hardened steel inserts into which sharp buttress-shaped grooves had been milled. The grooves were about 0.025 inch wide and 0.015 inch deep. The inserts were glued into the clamp jaws using ordinary epoxy. The dead load source of force maintained a constant stress despite small creep in the specimens.

For loading the small compression-only specimens, a piece of plexiglas of about 1/2-inch-square cross section was placed in each clamp of the vise. The facing surfaces of these two pieces of plexiglas were each fitted with a thin brass plate, about 1/2 by 1 inch, epoxied onto the plexiglas. A short length of stiff copper wire was soldered to the end of each brass plate for electric connection. The specimens were then held between these plates, with the silver-painted faces of the specimen in contact with the plates. The weight of the lever alone provided enough preload to hold the specimens securely for the low-stress data, and the 10-lb weight was added at suitable locations on the lever for the high-stress data.

The lever arrangement gave a maximum force multiplication of about 100, so with a 10-lb weight a maximum tension or compression force of about 1,000 lb was obtained. This was confirmed using a small compression load cell. An uncertainty of about $\pm 5\%$ was observed, due to friction in the loading device.

Dielectrometer

Capacitance and equivalent parallel conductance were measured using a Shering bridge driven by a sine-wave generator and detected by a tuned null detector. This apparatus was described in more detail earlier (James 1981).

Procedure

Data were taken in a lab held near 80° F and 30% relative humidity (RH). Specimens were brought into the laboratory from their conditioning rooms sealed in poly bags. The actuating lever of the loading vise was blocked in its raised position while the specimen was clamped into the vise. Data were then taken at each frequency, starting with the lowest, with the specimen unstressed and stressed.

Attempts to obtain data at a series of increasing stress levels were not successful because the data were too unstable and drifted as readings were made. Therefore, data were obtained only at near-zero stress (unstressed) and at the maximum stress available (for longitudinal grain) or the maximum estimated stress that the specimen could endure without yielding, for radial or tangential grain. Readings were made as quickly as possible to reduce the effect of drift. Typically, readings were repeated at the stressed and essentially unstressed condition two or three times in quick succession and averaged in order to best define the effect of stress apart from the effect of drift.

Specimens loaded parallel to the grain all withstood the maximum force of 1,000 lb. This represented a stress level of about 1,400 lb/in.² for the large specimens and about 3,600 lb/in.² for the smaller specimens. For specimens loaded across the grain, stress levels of about 600 lb/in.² for the oak and 400 lb/in.² for the Douglas-fir were not exceeded.

RESULTS AND DISCUSSION

The data are shown graphically (figs. 3-5) as the relative change in electric property resulting from the indicated mechanical stress, grouped for other variables such as MC, frequency, specimen type, and direction of stress. All data on the effect of stress were adjusted approximately to what they would have been if the specimen were the only capacitance in the circuit, by multiplying the raw data by a factor approximately equal to the ratio of the total capacitance to the specimen capacitance. Each data point is the average from three replicate specimens.

General Results

The effect of mechanical stress on the dielectric constant and electric conductance of wood was relatively small and variable. It depended strongly on such factors as MC, frequency, and grain direction. The effects of stress were not constant with time, but tended to increase if the load was maintained, much in the manner of creep. Frequently the change in properties resulting from the first application of load was substantially larger than subsequent

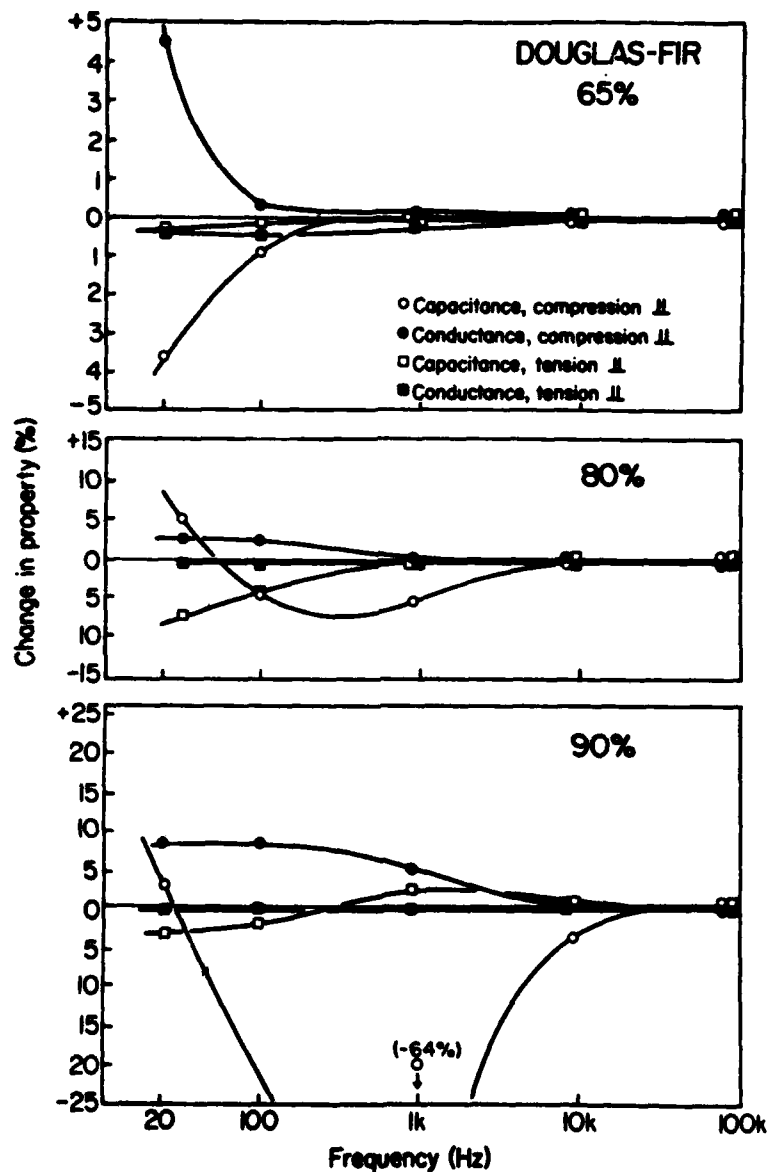


Figure 3.--Effect of a step change in stress on the dielectric properties of Douglas-fir conditioned at 65%, 80%, and 90% RH at various frequencies. Large specimen. (ML84 5206)

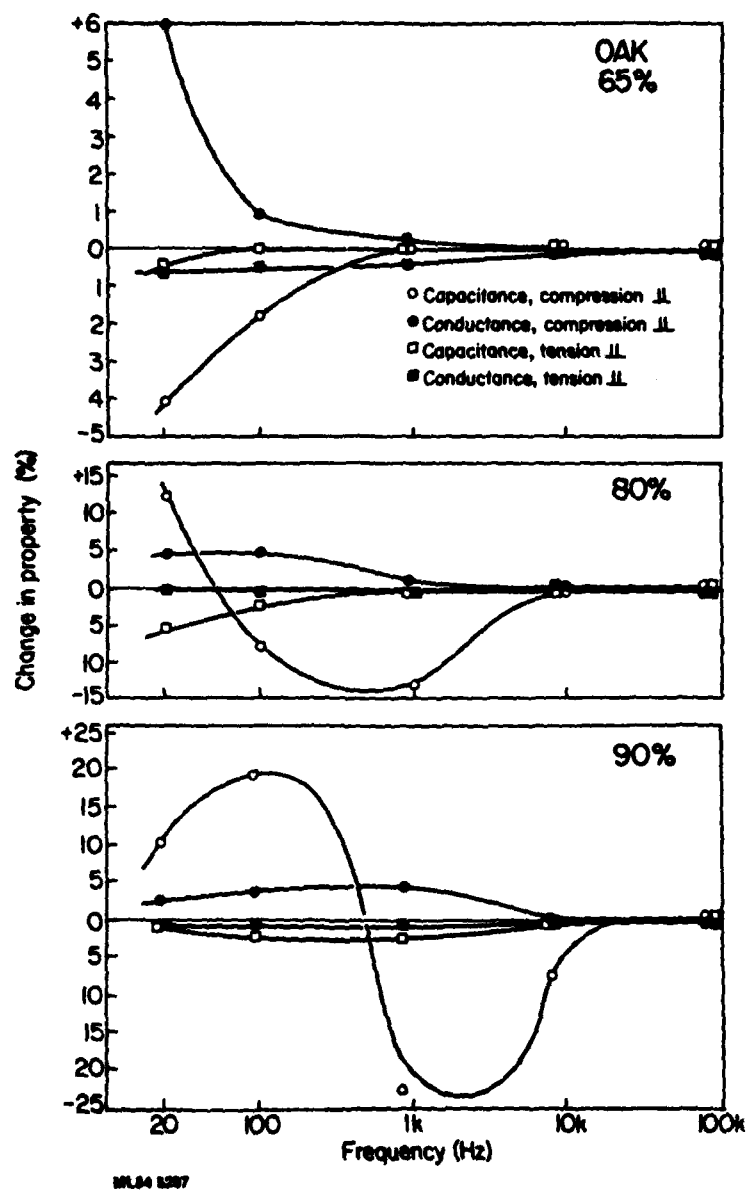
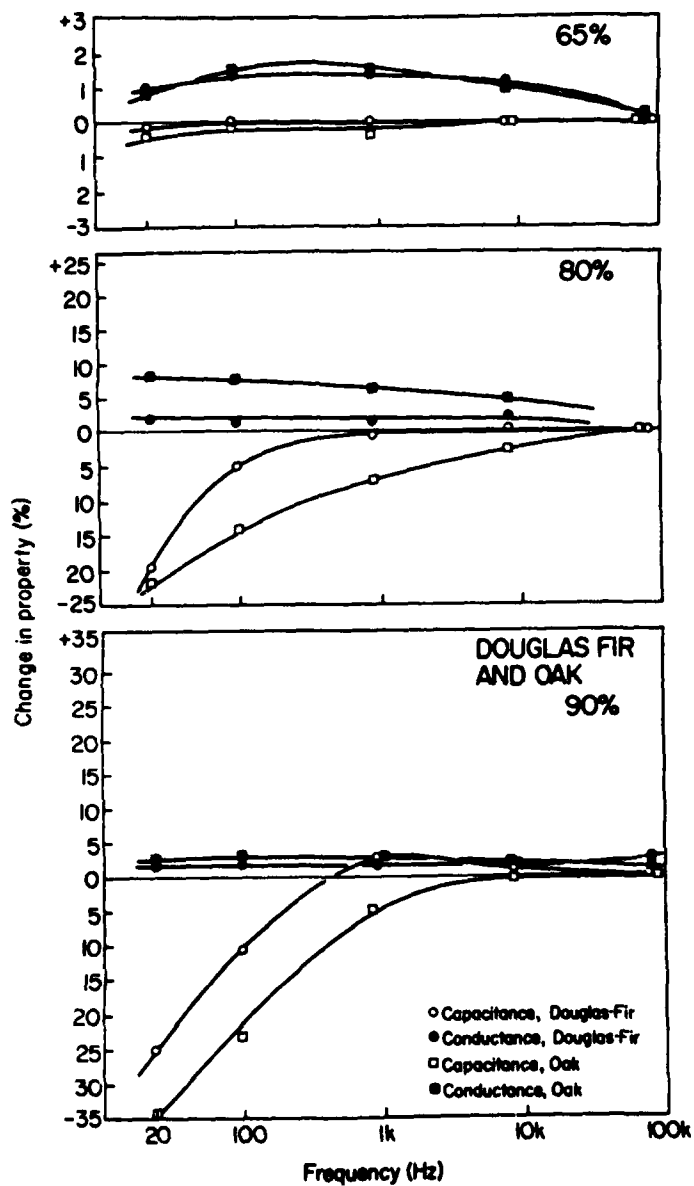


Figure 4.--Effect of a step change in stress on the dielectric properties of oak conditioned at 65%, 80%, and 90% RH at various frequencies. Large specimen.
(ML84 5207)



ML84 5208

Figure 5.--Effect of a step change in compression stress on the dielectric properties of Douglas-fir and of oak, conditioned at 65%, 80%, and 90% RH at various frequencies. Small Specimen.
(ML84 5208)

changes as the load was alternately applied and removed. After several load-unload cycles, the drift typically was small enough to permit a reasonable assessment of the direct effect of stress independent of the drift or creep. The drift, however, would clearly preclude any longtime relationship between stress and dielectric properties of wood.

For wood conditioned at 30% RH (about 6 or 7% MC) the effect was negligible. Also, the effect was very small at frequencies as high as 100 kHz, at any MC. For stress and electric field perpendicular to the grain, the effect was very small, as was the effect observed in a few exploratory experiments when stress was parallel to the grain and the electric field across the grain.

The effect of stress on dielectric properties generally increased as MC increased and frequency decreased, but at some combinations of species and MC this general result did not hold, and for some combinations of species and MC the effect of stress on dielectric constant (capacitance) changed sign as the frequency increased.

From elementary theory, the effect of stress would be expected to change sign as the stress changed from compression to tension or vice versa. The change in equivalent parallel conductance of wood stressed parallel to the grain was indeed of opposite sign when the stress was changed from compression to tension, but for many combinations of species, MC, and frequency, the change in dielectric constant (capacitance) was negative for both tension and compression. Also, in more moist specimens stressed perpendicular to the grain there was a tendency for compression to decrease the conductance. By contrast, for stress parallel to the grain, compression always increased conductance and tension decreased conductance.

Normal drying stresses in wood are almost entirely perpendicular to the grain, where the results of this study show the effect of stress on dielectric properties to be negligible. Therefore, the use of dielectric measurements to monitor drying stresses appears to be not feasible.

Dielectric Constant

Compression.--The data (figs. 3-5) show some consistent trends in the variation of dielectric constant with stress. In general, the effect of stress decreases as the frequency exceeds 1 kHz and is essentially nil at 100 kHz.

Also, the effect of stress on dielectric constant decreases as the MC decreases and is essentially nil at MC near 6%. Data taken on material conditioned at 30% RH, which has an MC near 6 or 7%, were not plotted because there was no detectable effect of stress.

Data taken on the larger specimens, where the stressed material was in a fringe field, sometimes showed a change in sign as the frequency increased. Specifically, compression sometimes increased the dielectric constant at 20 Hz, but decreased it at 100 Hz or 1 kHz. This observation is consistent with the understanding (James 1975) that in moist wood the predominant mechanism of polarization is interfacial at 20 Hz and dipole at 1 kHz. Interfacial polarization involves the migration of charge carriers within structural domains of the material, under the influence of an external electric field, and the consequent accumulation of charge at the domain boundaries. Interfacial polarization, therefore, could be enhanced by compressive stress due to increased density (reduced domain size) and conductivity of the wood, so the overall polarizability (dielectric constant) at 20 Hz could be increased by compression. At frequencies approaching 1 kHz interfacial polarization is overshadowed by dipole polarization, and dipole polarization would be expected to be suppressed by compressive stress due to restraint of the dipoles and to reorientation of the dipole axes away from the direction of maximum polarizability (Braybon 1953; Scott 1935).

Tension.--When these same specimens were subjected to tensile stress, it might be expected from the simple symmetry of the theory that the dielectric constant would be affected equally and opposite to the effect of compression. With most specimens, however, tensile stress reduced the dielectric constant, which of course is the same effect as with compression. Only in Douglas-fir conditioned at 90% RH did the tensile stress actually increase the dielectric constant; this occurred at frequencies of 1 and 10 kHz.

This dissymmetry in the affect of stress also was seen in the magnitudes; the effect of tensile stress generally was much less than that of compression.

The explanation and significance of the dissymmetry of stress-induced changes in dielectric constant of wood are not obvious, and not predicted from theory as presently developed. The effect of stress is generally considered to be in two major parts: the modification of interaction between neighboring

dipoles due to density changes, and the generation of dielectric anisotropy due to strain-induced reorientation of molecular dipoles. These two effects would usually be in opposite direction (see, for example, Treolar 1947), so the net effect of stress is essentially the difference of the two. It seems reasonable that the basic source of the observed effects in wood is the very complex, disordered nature of the polar arrays of the cellulose molecule, especially considering the large, complex modification of the properties of cellulose by adsorbed water. Specifically, the overall effect of strain-induced reorientation of the polar groups would be very hard to predict or to describe in a physically plausible theory. The application of the theory of stress birefringence to polyethylene (Crawford and Kolsky 1951) probably relates to wood about as well as any reasonable development of the theory, but again the extremely disordered nature of the dielectric properties of the cellulose molecule makes theoretical treatment a formidable task. The only conclusion that follows, therefore, is that the reason compression and tension do not produce equal and opposite effects on the polarizability of solid wood lies in the same basic dissymmetry in the long, kinky cellulose molecule.

Conductance

The equivalent parallel conductance of solid wood parallel to the grain consistently was increased by compression parallel to the grain and decreased by tension parallel to the grain. The change was much larger for compression than for tension. Previous experimental work (Bach 1967) showed that an increase in conductance across the grain resulted from a tensile stress along the grain. This result might be considered consistent with the present data, because the Poisson ratios of wood are such that a lateral compression results from a longitudinal tension. It is not consistent, however, because, as mentioned earlier, for direct stresses across the grain, I typically observed a small decrease in equivalent parallel conductance from a compressive stress. It should be mentioned that the equivalent parallel conductances observed here for moist wood increased slightly and smoothly with increasing frequency, which is consistent with real ionic conductance, not just equivalent dielectric loss. So the equivalent parallel conductances I report here are comparable to conductances directly measured by others.

Electrical conductance in wood is generally considered to be predominantly ionic. The conductance then depends on the charge carriers available per unit volume, the charge carried by each, the mobility of the charge carriers, and the dimensions of the material being considered (Brown et al. 1963). There would be, therefore, a change in conductance under stress due only to the change in dimensions of the specimen and the associated change in number of charge carriers per unit volume. In the present experiment, the linear strain expected to result from the experimentally applied stress would be 0.1% or 0.2%, so the direct effect of stress on conductance observed here should be of this same order. Clearly, under some conditions, the change in conductance was much more than this, which indicates a strong influence of stress on the mobility of the charge carriers as well. An additional change in basic number of charge carriers, or their average charge, resulting from the stress cannot be ruled out by present data, but this effect is theoretically unlikely.

The exact nature of electric conduction in wood has not been established. It is generally agreed that the ionic charge carriers migrate through the amorphous regions of the cellulose macromolecules. Under compressive stress parallel to the grain the cellulose chains in the amorphous regions would become more kinked and perhaps spread apart to expose more inner surface. There is evidence that electric conductance in wood is a surface phenomenon (Barkas et al. 1943), so the opening of the amorphous structure by longitudinal compression could increase ionic mobility. Tension parallel to the grain and compression across the grain would close the structure, reduce inner surface, and reduce conductance, as observed in this study. This is pure speculation, however, and the actual physical mechanism of electric conductance and its interaction with stress is yet unknown.

Specimen Differences

A puzzling aspect of the results of this study is the major difference in data between the two types of specimen. The differences between the specimens themselves can be summarized as follows: The smaller specimens experienced about 2-1/2 times the maximum stress of the larger specimens, and the smaller specimens were in a quasi-uniform electric field as opposed to a fringe field for the

large specimens. A minor difference was that the smaller specimens could be loaded only in compression.

The differences in dielectric response to stress parallel to the grain appear to be mainly that (1) compression suppressed the dielectric constant of the smaller specimens most strongly at 20 Hz, whereas in the larger specimens compression often enhanced the dielectric constant at 20 Hz; and (2) the effects of compression on the smaller specimens persisted to higher frequencies, with less overall effect of frequency, than it did for the larger specimens. In addition, at some conditions, most notably in specimens conditioned at 65% RH, the observed effect of stress was substantially less in the small specimens than in the large specimens, even though the small specimens experienced more than double the stress level.

The disparity in data between the two specimen types suggests the possibility that the effect of stress is not a linear function. I was not able to establish this linearity experimentally because the dielectric properties under stress drifted so rapidly with time. Attempts to observe the effect of stress at a series of increasing stress levels did, however, fail to indicate any nonlinearity. Specifically, the bridge unbalance signal increased fairly smoothly and roughly proportionally with increasing stress when the stress was increased quickly from zero to maximum. It follows that a nonlinear effect of stress is not a likely source of the difference between specimen types.

The only other obvious difference in experimental conditions between the two specimen types was the difference in electrode configuration and consequent difference in electric field geometry. The small specimens were in a nearly parallel electric field, while the larger specimens were in a fringe field with a substantial component of the field perpendicular to the grain (when the stress was parallel to the grain). Since measurements made with both specimen types showed very small effect of stress when the field was perpendicular to the grain, the expected effect of electric field geometry would be that the effect of stress would be larger for the small specimens. The data are not in accord with this expectation, so the specimen differences remain unexplained.

SUMMARY AND CONCLUSIONS

Under some conditions, the dielectric constant and equivalent parallel conductance of wood are changed by mechanical stress. The effect is negligible in wood as dry as 6 or 7% MC and practically negligible at frequencies as high as 100 kHz. The effect is very small for stress and/or electric field perpendicular to the grain. The effect of stress generally increases as the wood MC increases and as the frequency decreases, but under some conditions the effect on dielectric constant (capacitance) changes sign as frequency increases. The sign change occurs at frequencies where it is likely that the principal mechanism of polarization changes between interfacial and dipole.

The effect of stress on dielectric properties of wood is very unstable with time and appears to "creep" much as strain does under sustained loads. The creep in dielectric properties was observed at low stress levels, however where mechanical creep would be very small. Mechanical creep, therefore, is not a likely explanation for the dielectric creep.

This study reveals only the most elementary aspects of the effect of stress on dielectric properties of wood. The matter is apparently very complex, and many questions are not answered. It is reasonably clear, however, that the effect is very small for mechanical and electric stress across the grain, so the use of dielectric measurements to monitor drying stress appears to be not feasible.

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FIGURE CAPTIONS

Figure 1.--Specimens used in this study. Left: a large specimen before the central part was wrapped in plastic film, showing the silver paint electrodes. Center: a small compression-only specimen, also before being wrapped in plastic. Right: a large specimen showing the moisture barrier wrap.

Figure 2.--Two views of the loading vise used to apply either tension or compression stress to the specimens.

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